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# Structural Analysis of High-rpm Composite Propfan Blades for a Cruise Missile Wind Tunnel Model

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# STRUCTURAL ANALYSIS OF HIGH-RPM COMPOSITE PROPFAN BLADES FOR A CRUISE MISSILE WIND TUNNEL MODEL

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## SUMMARY

Analyses were performed on a high-speed composite blade set for the Department of Defense Propfan Missile Interactions Project. The final design iteration, which resulted in the CM2D-2 blade design, is described in this report. Mode shapes, integral order excitation, and stress margins were examined. In addition, geometric corrections were performed to compensate for blade deflection under operating conditions with respect to the aerodynamic design shape.


## INTRODUCTION

The Department of Defense is exploring the use of composite propfan blades for the propulsion of long-range cruise missiles. In conjunction with this effort, NASA Ames and NASA Lewis Research Centers cooperated to design and test a 0.55-scale wind tunnel model (fig. 1). The purpose of the wind tunnel model effort was to examine aerodynamic interactions between propfan blades and a cruise missile airframe.

A program overview and summary of the Department of Defense/NASA Propfan Missile Interactions Project is given in reference 1. A complete overview of the composite propfan blade project at NASA Lewis is given in reference 2.

The propfan configuration for the wind tunnel model consisted of one set of counter-rotating blades. There were two rows of blades, and each row contained six composite propfan blades.

Various blade sets were examined in the Propfan Missile Interactions Project, including the CM1 and CM2 series. The CM1 series is a high aspect ratio, low tip speed design, whereas the CM2 series is a low aspect ratio, high tip speed design (ref. 3). The "CM" portion of the blade naming convention indicates that the blade is designated for the cruise missile project. Each series includes the baseline geometry denoted as "CMn," where "n" is the series number (e.g., CM2). Variations in the baseline geometry (refs. 3 and 4) are denoted as "CMn$\alpha$," where "$\alpha$" is a letter indicating the geometry iteration (e.g., CM2D). Any changes in composite layups are denoted by "-m," where "m" is a number indicating the layup iteration (e.g., CM2D-2). This report describes the blade design of the CM2 series.

## BLADE DESCRIPTION

### Coordinate System and Setting Angle Definition

In the propfan blade coordinate system, the X-axis is oriented in the spanwise direction of the blade, as shown in figures 2 and 3 for the forward and aft blades, respectively. The origin is located at the blade's center of rotation, with rotation occurring about the Y-axis. All forward blades rotate about the positive Y-axis, and aft blades rotate about the negative Y-axis (following the right-hand-rule convention).

The setting angle of the blade is the angle between the blade chord (at the 3/4 radial station) and the X-Z plane (rotating about the X-axis). The 3/4 radial station is the section of the blade located at three-fourths of the total radial distance between the axis of rotation and the tip of the blade. For all CM2 blades, this radial station is 5.34 in. from the axis of rotation. The blade setting angles are 55.9° and 52.4° for the CM2D-2 forward and aft blades, respectively (figs. 2 and 3).

## Ply Definition

The propfan blades were designed with composite laminae, or plies, of unidirectional Thornel (Amoco) fibers embedded in a matrix of Fiberite 948A1 (Fiberite) epoxy (table I). These plies are stacked in a sequence of alternating ply orientation angles. The ply orientation angle is the angle of the unidirectional fibers with respect to a global X reference axis that corresponds to the blade's X-axis.

The outside plies cover the entire blade surface. The number of plies through the thickness of the blade is greatest near the center of the chord at the base, and it decreases traversing out from the span and toward the edges. The ply profiles become smaller as they get closer to the midplane of the blade. For a detailed description of the ply profile generation and fabrication, see references 4 and 5.

The ply orientation stacking sequence starts with two plies aligned with the reference axis, followed by one ply rotated 45° counter clockwise, two additional plies aligned with the reference axis, and one ply rotated 45° clockwise. The sequence, which is symmetric about the blade's midplane surface, starts at the outer surfaces of the blade and repeats until the midplane of the blade is reached. This particular stacking sequence is denoted by $[0_2/45/0_2/\text{-}45/...]_S$, with the ellipse indicating that this progression repeats until the midplane of the blade is reached. On the basis of experience with similar composite blade designs, this alternating sequence was selected to obtain a balance between bending and torsional strength that would maximize the structural integrity of the blade.

As shown in figure 4, the shank of the blade consists of a cylindrical stainless steel shell with a composite tab running through it (ref. 4). Composite filler material was added to fill the area between the shell and the tab.

## CM2 Series Overview

The CM2 blade set is a low aspect ratio, high-speed design with specified operating speeds of 9650, 12 060, and 14 475 rpm that produce blade tip velocities of 600, 750, and 900 ft/sec, respectively. The speed used in the aerodynamic design of the CM2 series was 14 475 rpm (ref. 3). Cold shape corrections, which modify the blade geometry to account for pressure and centrifugal loading, were performed at the maximum design speed of 14 475 rpm, and stress analyses were performed at a maximum overspeed condition of 16 807 rpm. This process is discussed further in the ANALYSIS DESCRIPTION AND METHODOLOGY section.

The CM2 blade has a span of 3 in. with the base located at 4.25 in. and the tip at 7.25 in. radially outward from the axis of rotation. Six variations of the CM2 design, as discussed in references 3 and 4, were examined. These include the CM2, CM2A, CM2B, CM2C, CM2D, and CM2E blade geometries. The CM2D-2 blade, which was also examined, is geometrically the same as the CM2D blade but has different ply orientation angles.

The ply orientation stacking sequence of all CM2 series blades is $[0_2/45/0_2/\text{-}45/...]_S$. The CM2D-2 blade has the same stacking sequence except that the ply orientation angles are rotated by 20°, denoted as $[20_2/65/20_2/\text{-}25/...]_S$.

## ANALYSIS DESCRIPTION AND METHODOLOGY

Programs used in the structural analysis of the CM2 blade design include COBSTRAN (COmposite Blade STRuctural ANalyzer) (refs. 6 and 7), MSC/NASTRAN (Macneal Schwendler Corporation NASA STRuctural ANalysis) (refs. 8 and 9), and PDA/PATRAN (PDA) (ref. 10). COBSTRAN generates finite element mesh and material data for input to MSC/NASTRAN. It uses laminate theory calculations to generate homogeneous, anisotropic material properties for MSC/NASTRAN and calculates individual ply stresses on the basis of MSC/NASTRAN stress output. PDA/PATRAN is used in the preprocessing of blade models and the postprocessing of analysis results.

The analysis methodology for the CM2 blade design is similar to that for the CM1 blade design detailed in reference 11. A brief overview of this methodology follows.

The design process starts with the aerodynamic analysis and generation of airfoil sections at various spanwise locations (ref. 3). These sections are transferred to a CAD system where a surface model of the blade is generated. The CAD system then creates midplane coordinates and thickness data (ref. 4) used in the input deck for COBSTRAN. Composite material properties and ply-orientation stacking sequence data complete the COBSTRAN input deck. COBSTRAN generates the material properties (MAT2 cards) and a finite element mesh (GRID cards and CTRIA3 element cards) for the body of the blade in MSC/NASTRAN bulk data format. For all CM2 finite element models, COBSTRAN generates 456 CTRIA3 elements and 260 grids. Because the number of plies varies with the blade thickness, each element has its own associated MAT2 card. The MAT2 cards represent anisotropic material properties based on reduced axial and bending stiffnesses.

The finite element mesh is visually verified with PATRAN. Then PATRAN is used to add a shank to the finite element model. The shank region is modeled with 1 bar (CBAR) element representing the metal shell, 1 tapered beam (CBEAM) element representing the filler material, and 12 triangular plate (CTRIA3) elements representing the tab. The material properties used for the tab elements are the same as the elements generated by COBSTRAN directly above the shank region. Four rigid bar (RBAR) elements are used to tie the metal shell (CBAR element) to the outer edges of the tab (CTRIA3 elements). The blade is constrained at the base of the metal shell (CBAR element) by one single point constraint (SPC) card that fixes all 6 degrees of freedom. Pressure loads (ref. 3) are applied to the body of the blade to complete the bulk data deck for MSC/NASTRAN.

An eigenvalue analysis, using MSC/NASTRAN, is then performed on the blade set. This analysis consists of running a 0 rpm (MSC/NASTRAN solution 3) eigenvalue analysis and a nonlinear displacement solution with eigenvalue extraction at three operating speeds (MSC/NASTRAN solution 64/63, see ref. 9). Then Campbell diagrams are generated from the natural frequency data to examine integral order crossings of the blade natural frequencies. They show how the blade natural frequencies (cycles/second, or hertz) correspond to the rotational speed (revolutions per minute) of the blades. Integral order crossings are those points where the natural frequency is an integer multiple of the rotational speed. For example, if a blade operates at 200 rev/sec (12 000 rpm), the first integral order crossing will be at 200 Hz, the second at 400 Hz, the third at 600 Hz, and so forth. It is important to avoid continued operation of the system at rotational speeds where the blade natural frequency is an integer multiple of this rotational speed. If there is insufficient structural damping in the system, a forced excitation can feed energy into the blade, resulting in blade failure.

The engine order excitations of concern in this system are due to wakes generated by angle of attack, wings, fins, and blade passage interactions. These generate 1, 2, 4, and 12 excitations per revolution, respectively (as described on the Campbell diagrams). Modal data are then used to determine the aeroelastic stability of the blade (ref. 12). If the blade is stable, a cold shape correction, as described below, and stress analysis are performed.

The blade cold shape refers to the geometry of the blade in the absence of loading. The hot shape refers to the geometry of the blade after deflection due to centrifugal and pressure loading. The aerodynamic geometry initially supplied represents the desired shape of the blade at aerodynamic design operating conditions (14 475 rpm with appropriate pressure loading). However, deflections due to loading move the blade away from this desired aerodynamic geometry. Deflections are compensated for by an iterative cold shape correction (ref. 11) that is performed at the maximum design speed of 14 475 rpm. This correction adjusts the blade shape under loading to be same as the aerodynamic design geometry. Therefore, the new model represents the corrected cold shape of the blade, and when loading is applied to the this new model (cold shape), the deflected shape (hot shape) will be equivalent to the aerodynamic design geometry.

A nonlinear displacement solution at the maximum overspeed condition of 16 807 rpm is then performed using MSC/NASTRAN with subsequent COBSTRAN postprocessing. COBSTRAN generates ply stress and strain data as well as minimum margins of safety, as defined by the Hoffman failure criteria (ref. 6), for all of the blade plies.

At this point the analysis is complete if no integral order, stability, or stress problems are indicated. If problems exist, however, composite ply parameters, such as ply orientation, can be varied or a new geometry can be examined. The analysis procedure is repeated whenever the blade is modified.

## ANALYTICAL RESULTS FOR CM2

The following represents the analysis used to obtain the CM2D-2 blade design. Included in this section are CM2D and CM2D-2 Campbell diagrams and mode shapes, CM2D-2 cold shape corrections, CM2D-2 stress results, and CM2D-2 margins of safety.

COBSTRAN was initially run to generate the finite element mesh and material properties cards for all CM2 designs. PATRAN was then used to add the shank. The finite element mesh for the CM2D-2 forward and aft blades is shown in figure 5, and the composite material properties used in COBSTRAN are shown in tables I and II.

### CM2D and CM2D-2 Campbell Diagrams and Mode Shapes

Initially, an eigenvalue analysis with MSC/NASTRAN was performed on all CM2 designs at 0, 9650, 12 060 and 14 475 rpm. Campbell diagrams were then generated for each of the blade sets. Modal displacement and frequency data from the eigenvalue analysis were transferred to a group of aeroelasticity researchers, who performed an aeroelastic stability analysis on each of the blade sets (ref. 12).

The CM2D blade was predicted to provide the most aeroelastically stable design (ref. 12) while minimizing engine order excitation problems. The Campbell diagrams for the CM2D forward and aft blades are shown in figures 6 and 7 with corresponding normal mode shapes in figures 8 and 9. The predicted natural frequencies of the CM2D blade set are sufficiently distant from the integral order crossings at the three operating speeds (figs. 6 and 7).

The mode shapes of concern for integral order crossings are those that are in the range of the Campbell diagrams. These are modes 1 to 3 for the CM2D forward blade, which represent first bending, first torsion, and second bending, respectively (fig. 8). The CM2D aft blade mode shapes are modes 1 to 4, which represent first bending, first torsion, second bending, and second torsion, respectively (fig. 9).

The ply orientation angles of the CM2D blade were rotated by 20° to determine the effect on aeroelastic stability. This new blade was denoted as CM2D-2. An eigenvalue analysis, as stated earlier, was performed on the CM2D-2 blade followed by an aeroelastic stability analysis (ref. 12). Campbell diagrams for CM2D-2 forward and aft blades are shown in figures 10 and 11 with corresponding mode shapes in figures 12 and 13.

It should be noted that mode 1 moved slightly closer to the 4th engine order line at 14 475 rpm and that mode 2 moved slightly closer to the 12th engine order line at 9650 rpm for both the forward and aft blades (figs. 10 and 11). This condition is less desirable than that for the CM2D blade. The aeroelastic stability analysis, however, indicates that the CM2D-2 blade is more stable than the CM2D blade (ref. 12). Because the operating ranges can be varied, the operating point can be moved away from engine order crossings if deemed necessary. Therefore, it was decided to use the more aeroelastically stable CM2D-2 blade.

The mode shapes in the range of the Campbell diagrams are modes 1 to 3 for both CM2D-2 forward and aft blades. These represent first bending, first torsion, and second bending, respectively (figs. 12 and 13).

Preliminary holography test results (ref. 13) indicated that modal frequencies, and respective Campbell diagrams, are highly dependent on the method used to model and constrain the shank of the blade. Because of schedule considerations, a detailed model of the shank region could not be made. The mode shapes that are used in the aeroelastic stability analysis, however, seem to be less dependent on the shank modeling. Great care should be taken in modeling the shank area to achieve accurate modal frequencies.

## CM2D-2 Cold Shape Correction

The cold shape iteration sequence was performed using a MSC/NASTRAN nonlinear displacement solution at 14 475 rpm with the corresponding steady state air loads applied to the blade. The solution converged for both the forward and aft blades after three iterations. The convergence criteria required the hot shape to be within 0.001 in. of the aerodynamic design geometry.

The blade twist and displacement for the CM2D-2 blades are shown in tables III and IV. These tables represent the change between the cold and hot shape at the tip and 3/4 radial station of the blade. The twist represents the rotation of the respective section about the positive X-axis.

Campbell diagrams were recalculated with the corrected geometry. No significant change occurred between the Campbell diagrams or mode shapes for the original and corrected cold shape models. This result was expected because the difference between the hot shape and cold shape models is very small.

## CM2D-2 Stress and Margins

A nonlinear displacement solution using MSC/NASTRAN with subsequent COBSTRAN postprocessing was performed on the CM2D-2 blade for the steady state air load at the maximum overspeed condition of 16 807 rpm. COBSTRAN generated stress, strain, and minimum margins of safety for all plies in the blades.

Longitudinal stresses (in the direction of the fiber) of the outer plies are shown in figures 14 and 15 for the CM2D-2 forward blade and in 16 and 17 for the aft blade. The longitudinal stresses are mainly in tension for the outer ply pressure side and in compression for the outer ply suction side, as expected.

The minimum margins of safety for the CM2D-2 forward and aft blades, calculated using the Hoffman failure criteria, are shown in figures 18 and 19, respectively. The minimum margins occur at the blade's leading and trailing edges. The margins and stress levels at the edges are known to be artificially high because of interpolation errors in COBSTRAN where the blade thickness approaches zero. The significant minimum margins are those in the shank area. These are in excess of seven, and are considered acceptable. The design criteria for this blade was a minimum margin of five. The CM2D-2 blade design exceeds the minimum margin design criteria.

Actual minimum margins should be higher than predicted margins in the shank region because of the actual fabricated geometry of the blades. The shank region consists of additional plies that form a transition fillet between the shank and the blade body. These additional plies are not accounted for in the analysis (fig. 4).

## CONCLUSIONS

Mode shapes, integral order excitations, and stress margins were examined for the CM2 series blade design. Of the variations in the CM2 series, the CM2D-2 blade set represents a structurally sound blade design while maintaining aeroelastic stability. Margins of safety for this blade are adequate and indicate no significant concern for failure.

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TABLE I. - COMPOSITE MATERIAL PROPERTIES

| | |
|---|---|
| Fiber | Thornel T-300 (6K) untwisted |
| Matrix | Fiberite 948A1 epoxy, 250 °F cure temperature |
| Fiber volume ratio | 0.604 |
| Weight density, lb/in.$^3$ | $0.560\times10^{1}$ |
| Longitudinal modulus, lb/in.$^2$ | $0.194\times10^{8}$ |
| Transverse modulus, lb/in.$^2$ | $0.120\times10^{7}$ |
| Shear modulus, lb/in.$^2$ | $0.700\times10^{6}$ |
| Poisson's ratio | 0.310 |

TABLE II. - COMPOSITE PLY STRENGTHS

| | |
|---|---|
| Longitudinal tensile strength, lb/in.$^2$ | $0.266\times10^{6}$ |
| Longitudinal compressive strength, lb/in.$^2$ | $0.266\times10^{6}$ |
| Transverse tensile strength, lb/in.$^2$ | $0.930\times10^{4}$ |
| Transverse compressive strength, lb/in.$^2$ | $0.930\times10^{4}$ |
| Intralaminar shear strength, lb/in.$^2$ | $0.130\times10^{5}$ |

TABLE III. - CM2D-2 FORWARD BLADE TWIST AND DISPLACEMENT

| Location | Displacement, in. | | | Twist, deg |
|---|---|---|---|---|
| | ΔX | ΔY | ΔZ | |
| Leading edge at tip | 0.0025 | 0.0175 | 0.0220 | 0.11 |
| Leading-edge at 3/4 radial station | .0010 | .0017 | .0034 | .28 |

TABLE IV. - CM2D-2 AFT BLADE TWIST AND DISPLACEMENT

| Location | Displacement, in. | | | Twist, deg |
|---|---|---|---|---|
| | ΔX | ΔY | ΔZ | |
| Leading edge at tip | 0.0022 | 0.0176 | 0.0219 | -0.07 |
| Leading-edge at 3/4 radial station | .0014 | .0005 | .0005 | -.11 |

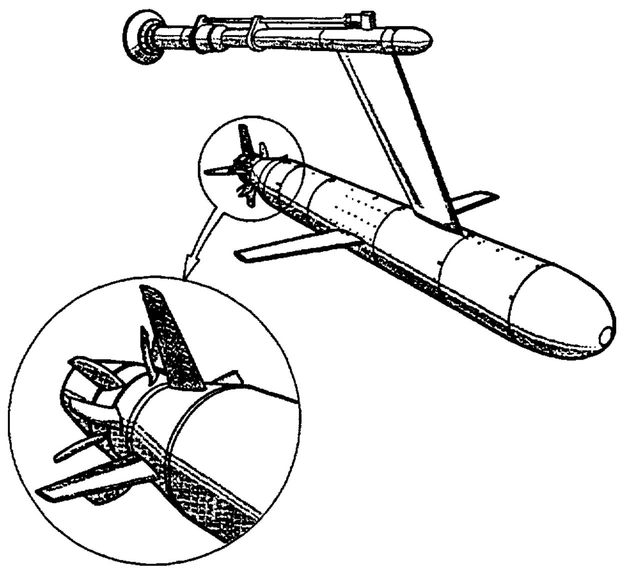

Figure 1.—Propfan Missile Interactions Project.

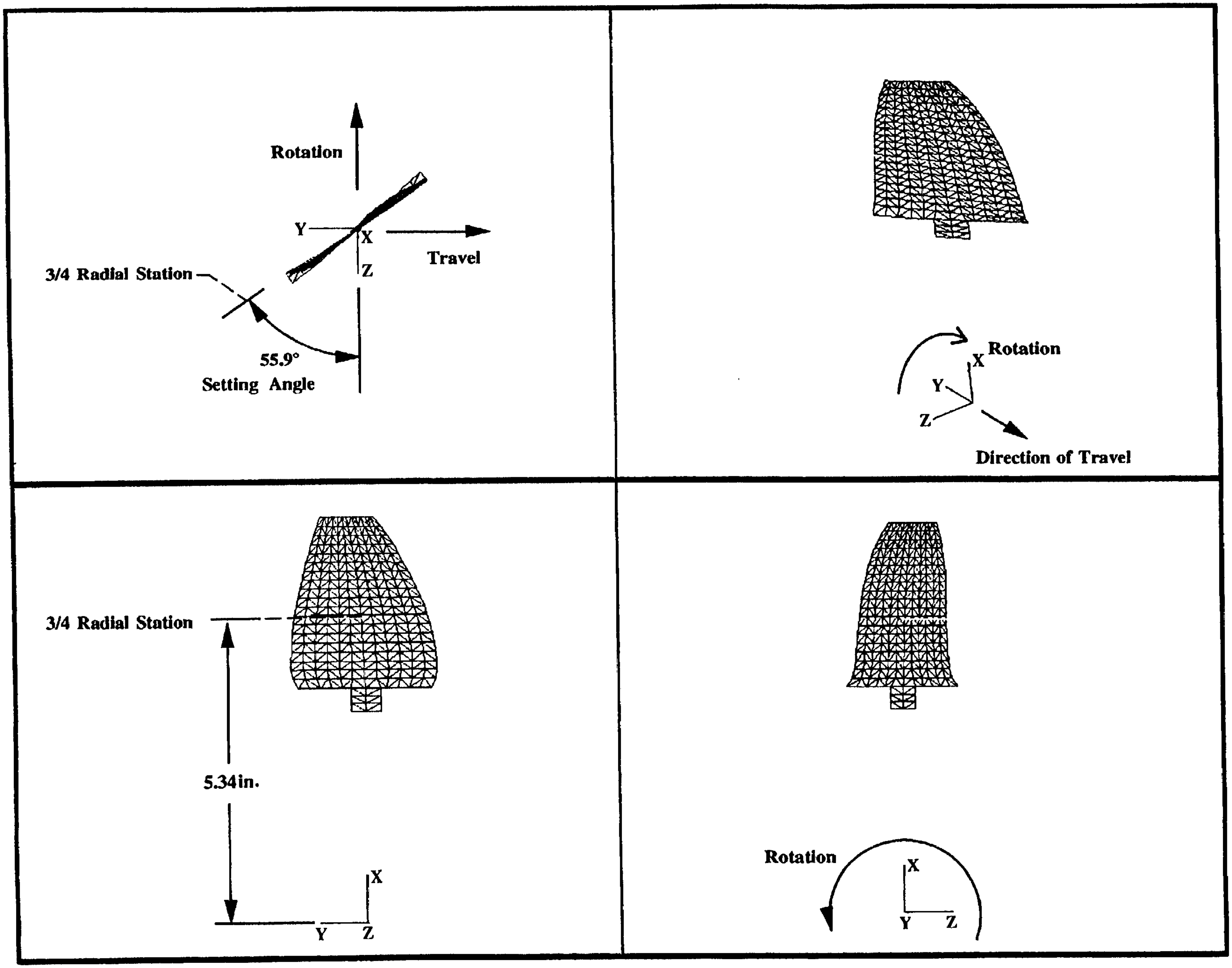


Figure 2.—CM2D-2 forward blade orientation.

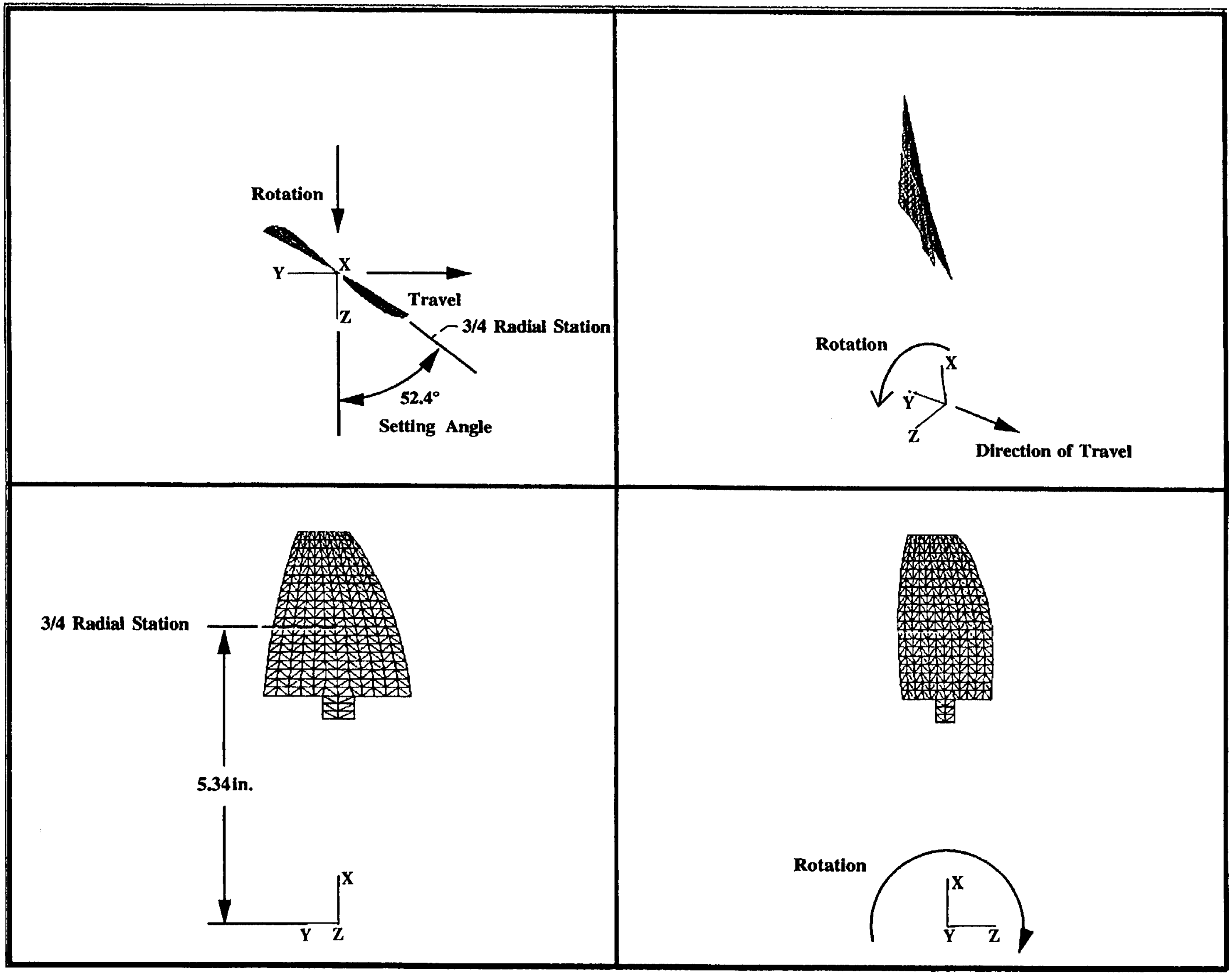


Figure 3.—CM2D-2 aft blade orientation.

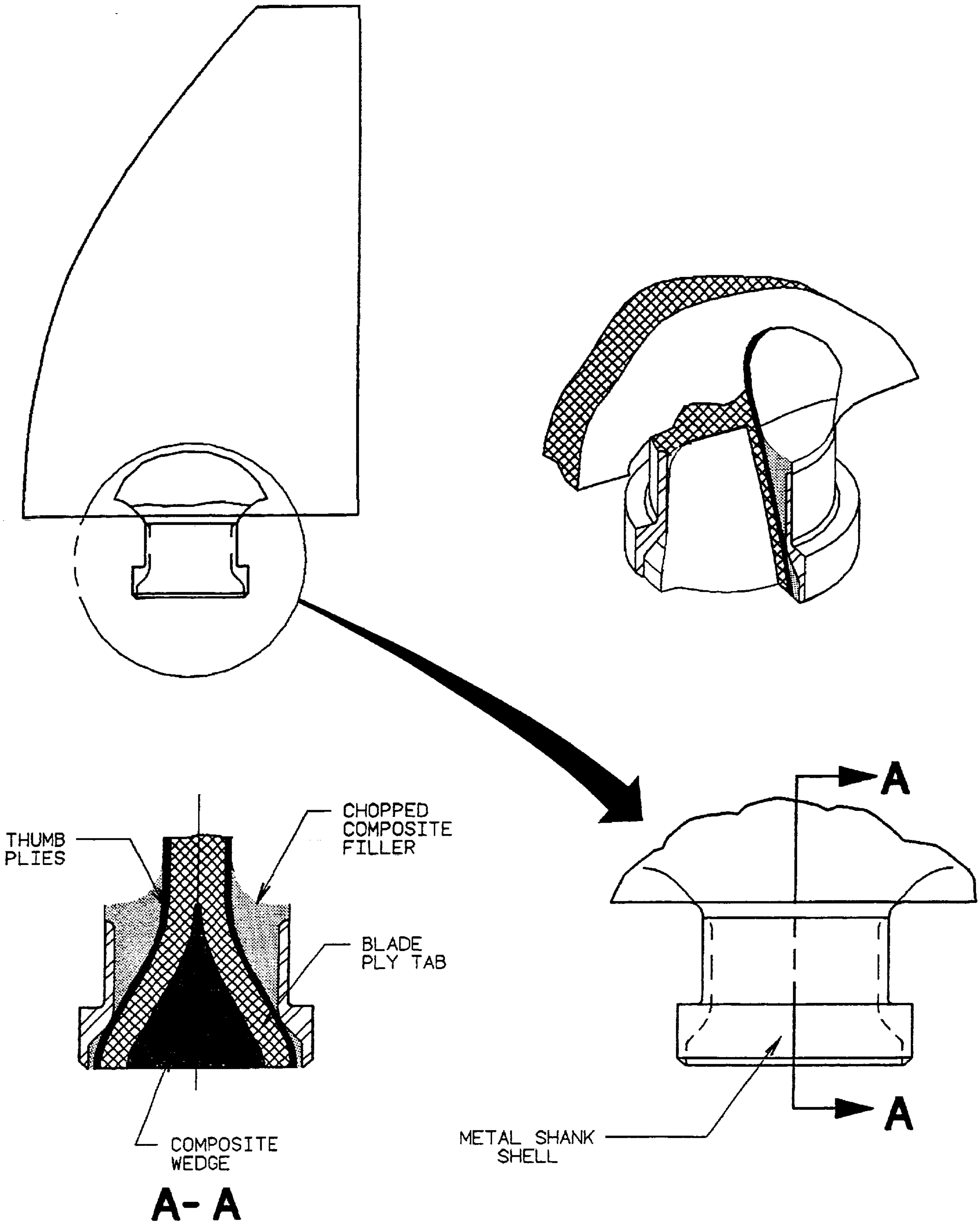


Figure 4.—CM blade metal-shell-to-airfoil attachment design.

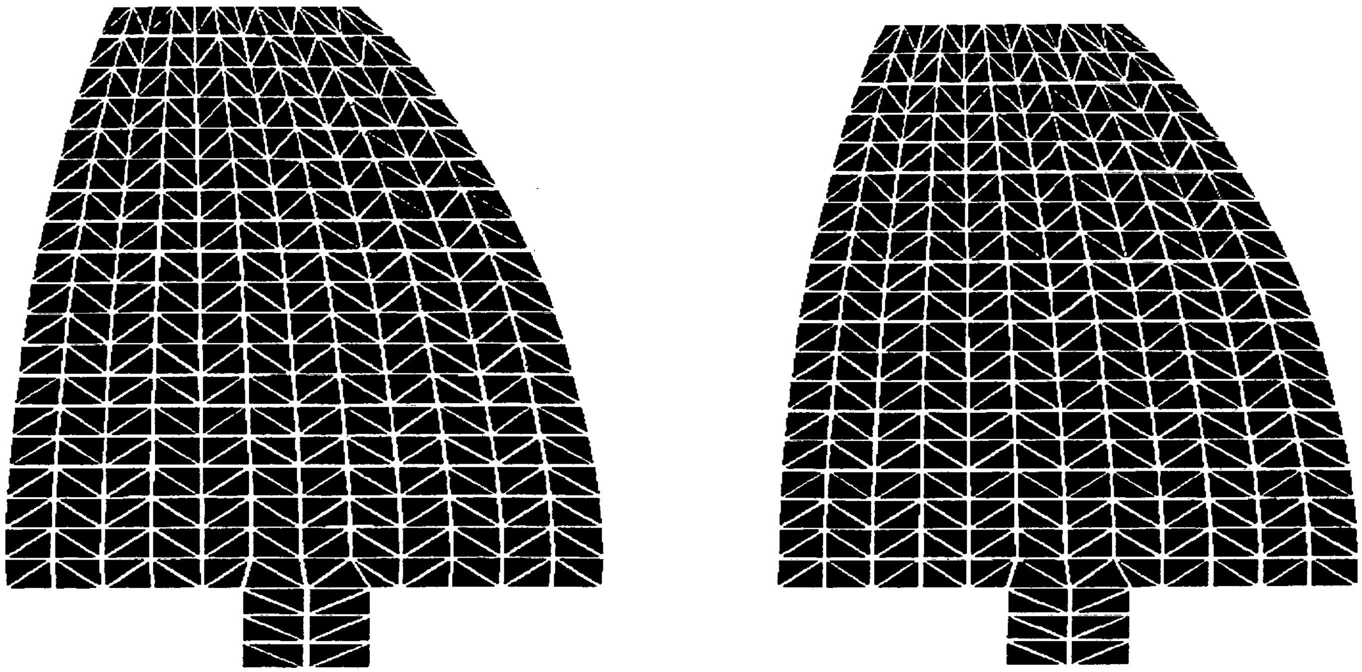


Figure 5.—CM2D-2 finite element meshes.

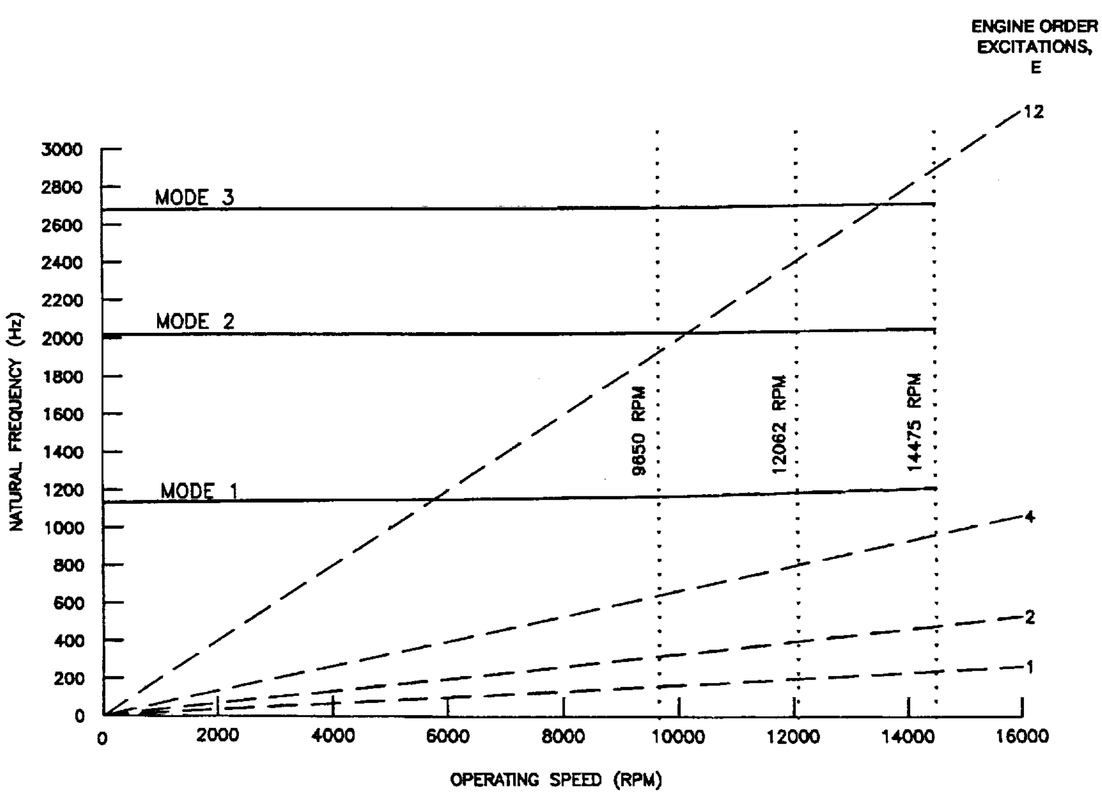


Figure 6.—CM2D forward blade Campbell diagram.

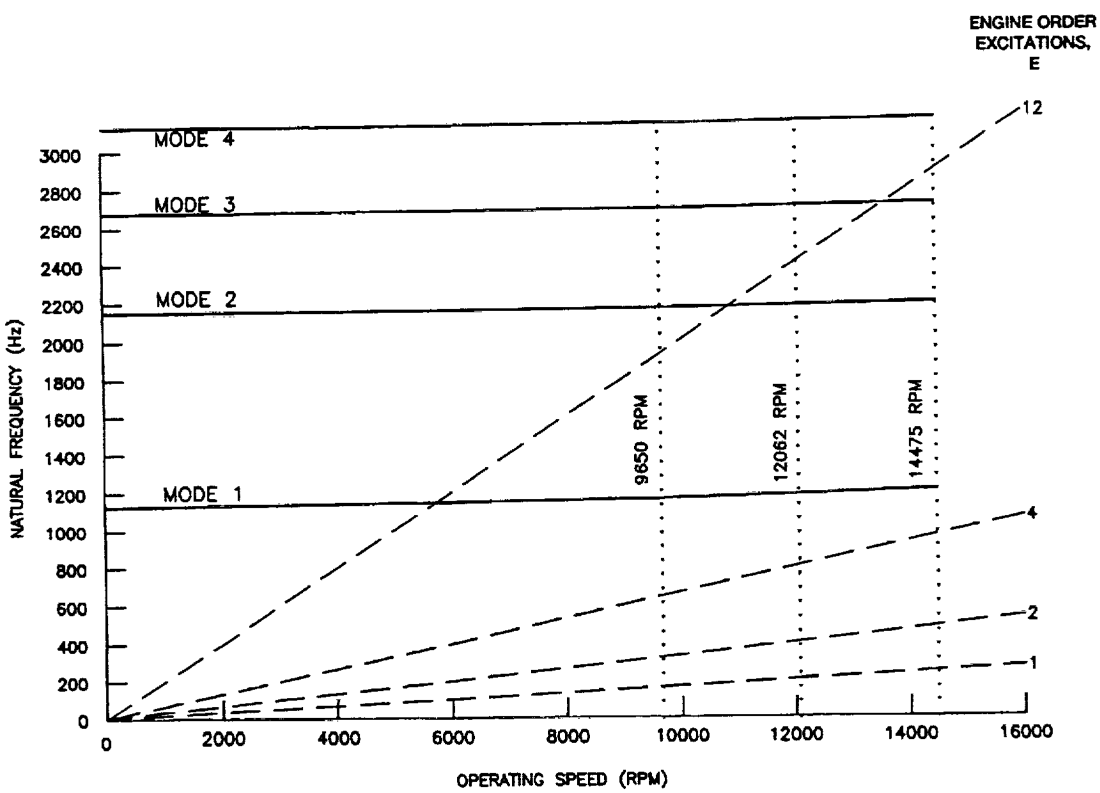


Figure 7.—CM2D aft blade Campbell diagram.

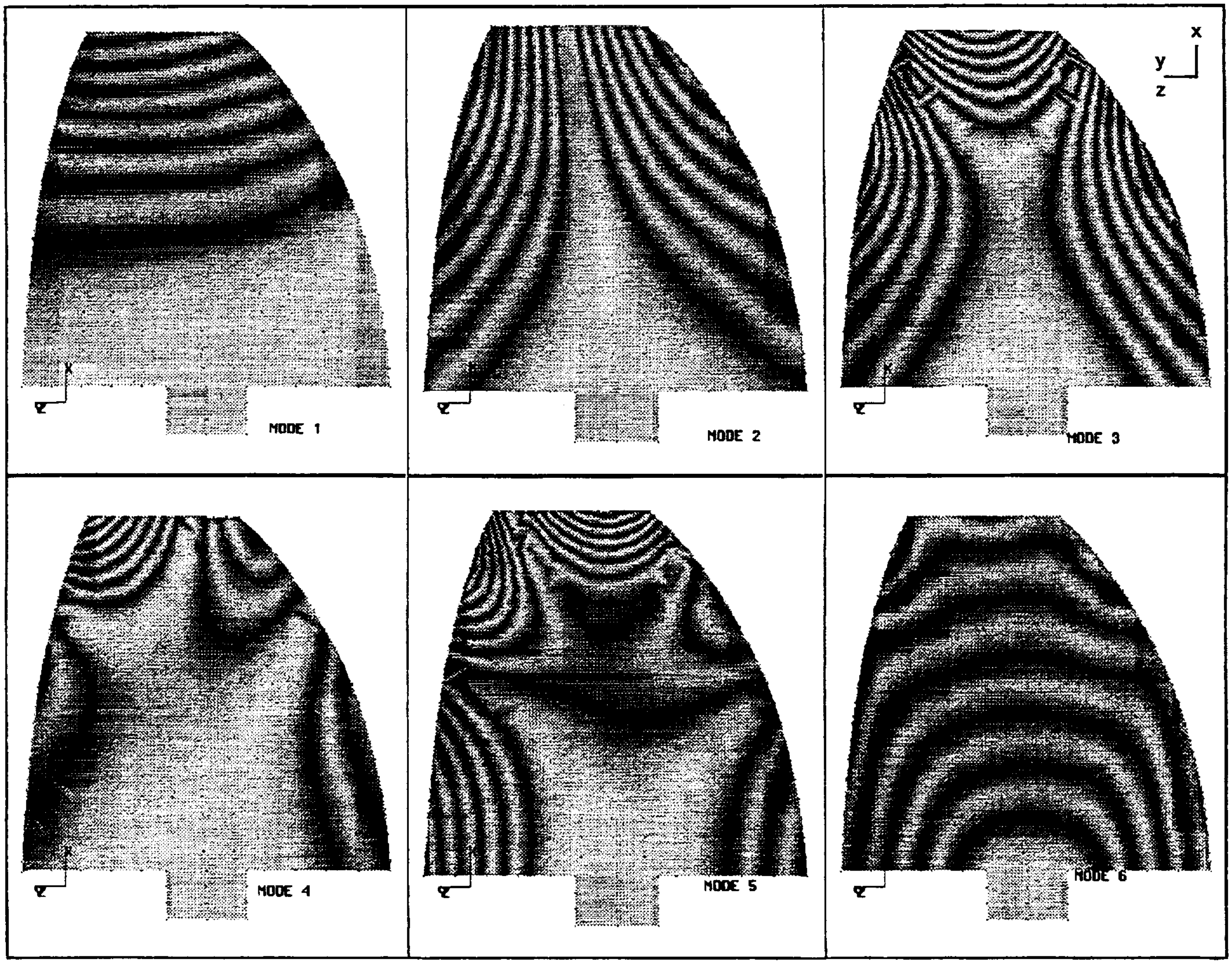


Figure 8.—CM2D forward blade mode shapes.

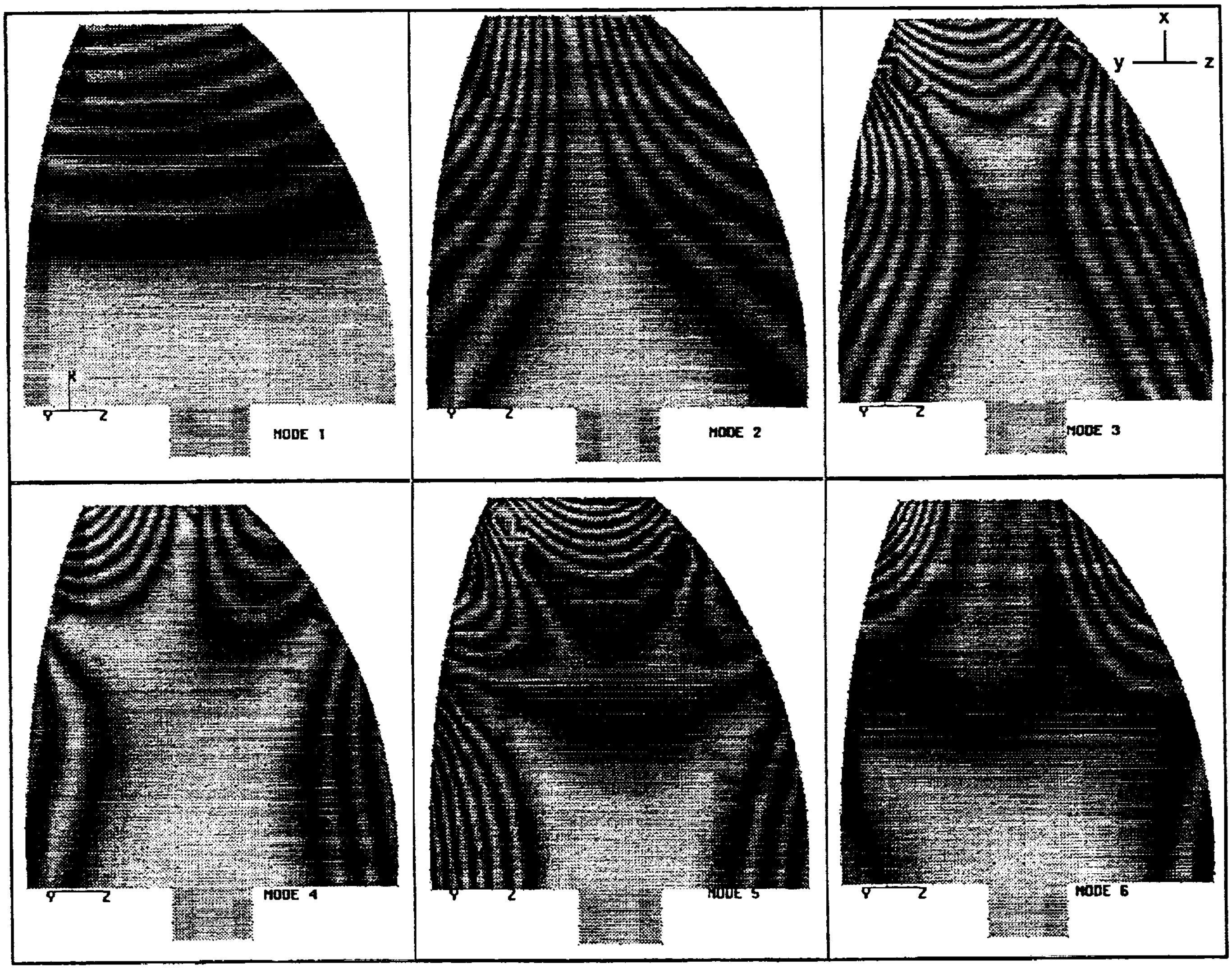

Figure 9.—CM2D aft blade mode shapes.

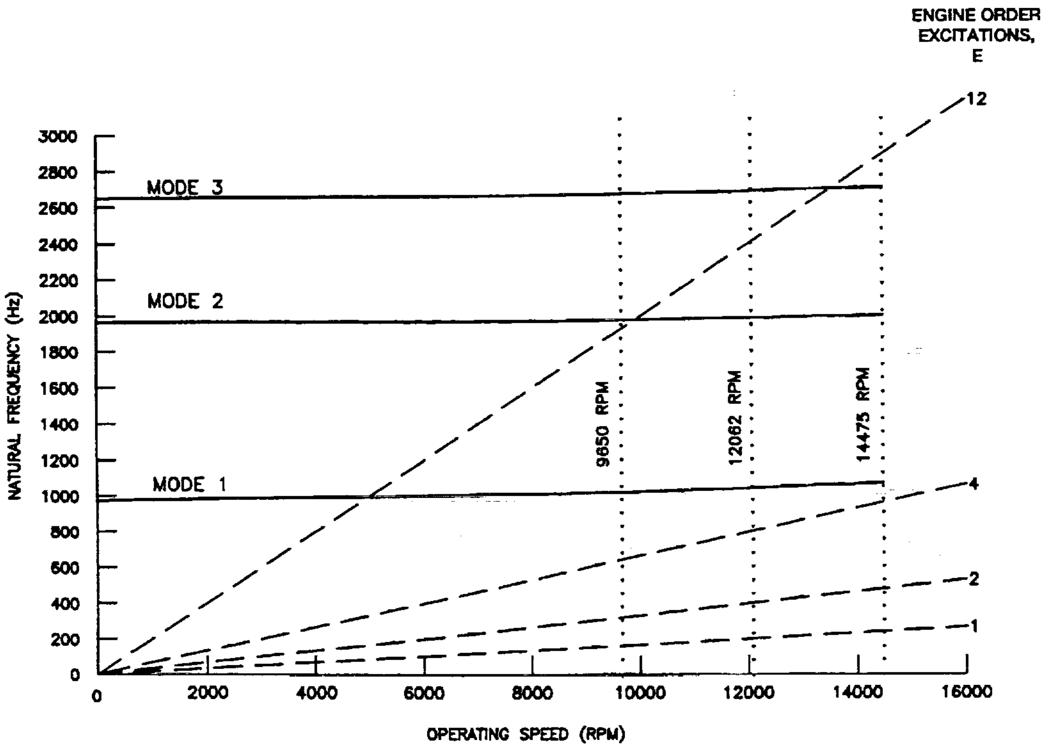


Figure 10.—CM2D-2 forward blade Campbell diagram.

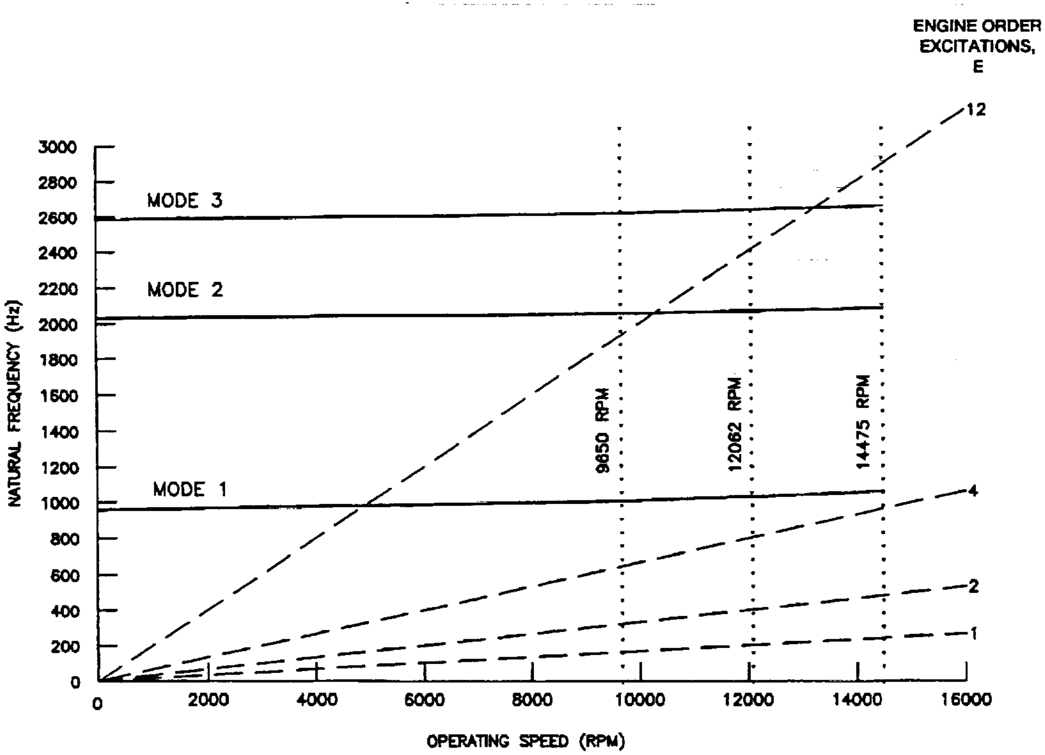


Figure 11.—CM2D-2 aft blade Campbell diagram.

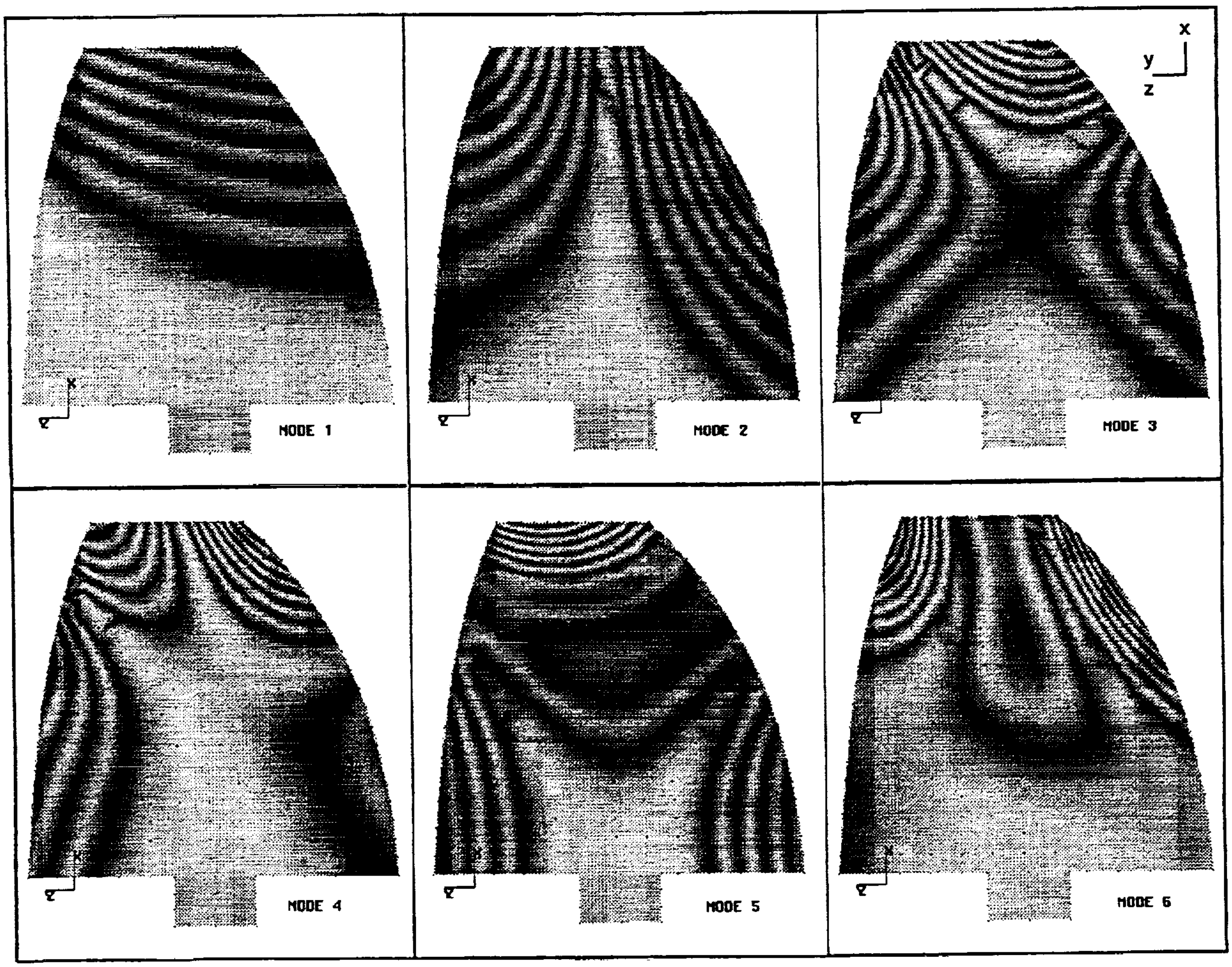


Figure 12.—CM2D-2 forward blade mode shapes.

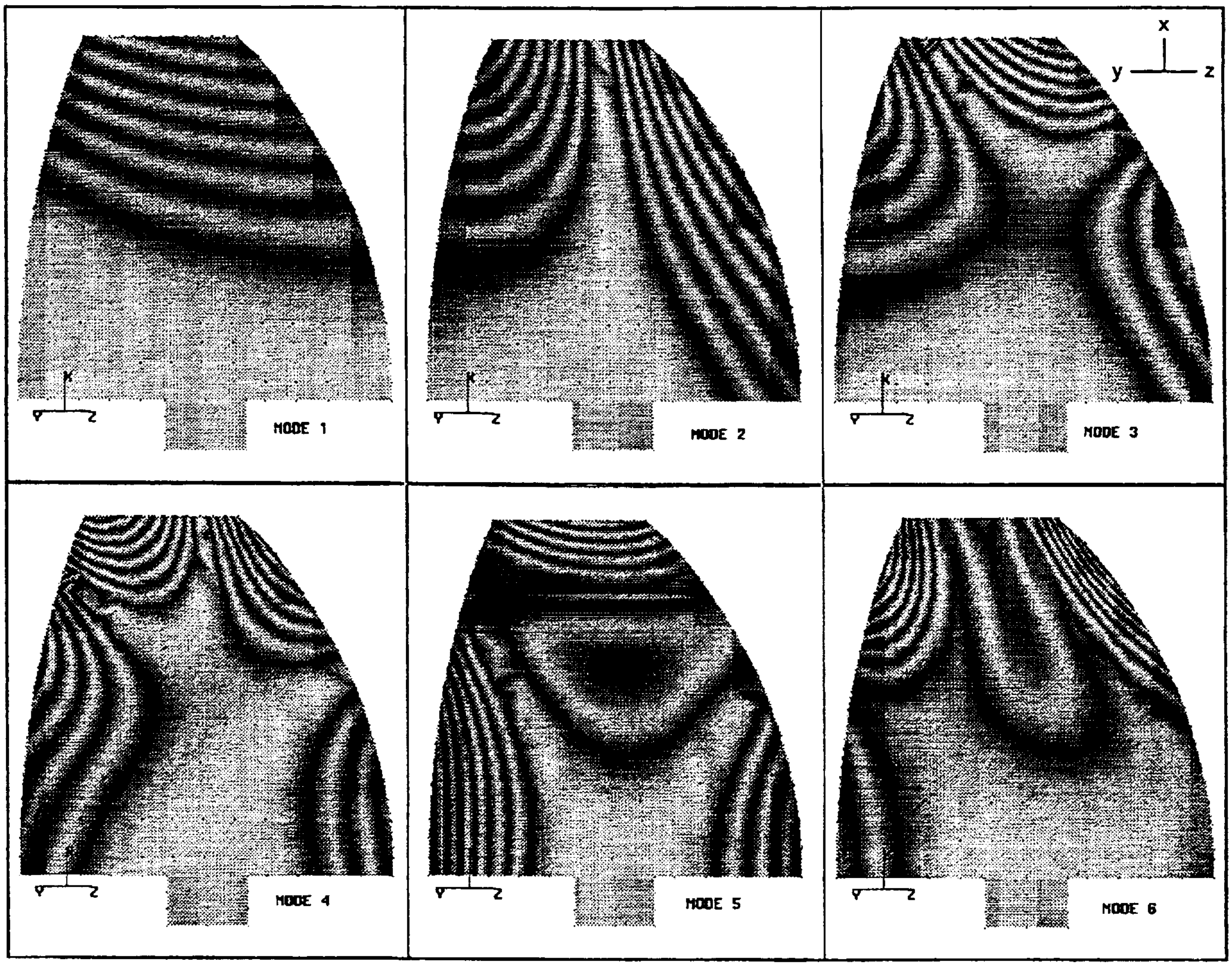


Figure 13.—CM2D-2 aft blade mode shapes.

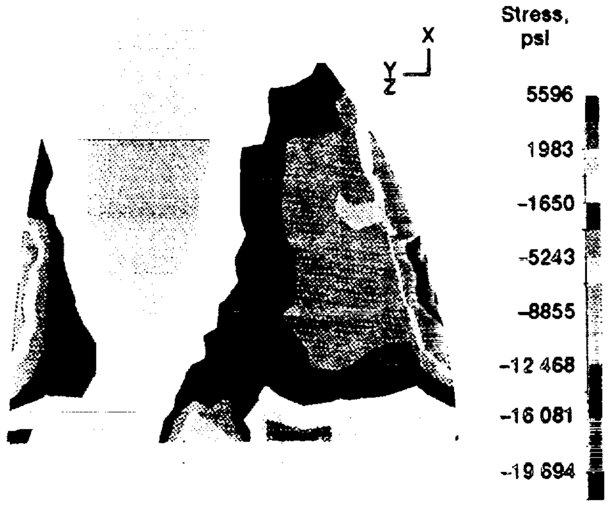


Figure 14.—CM2D-2 forward blade longitudinal stress (suction side).

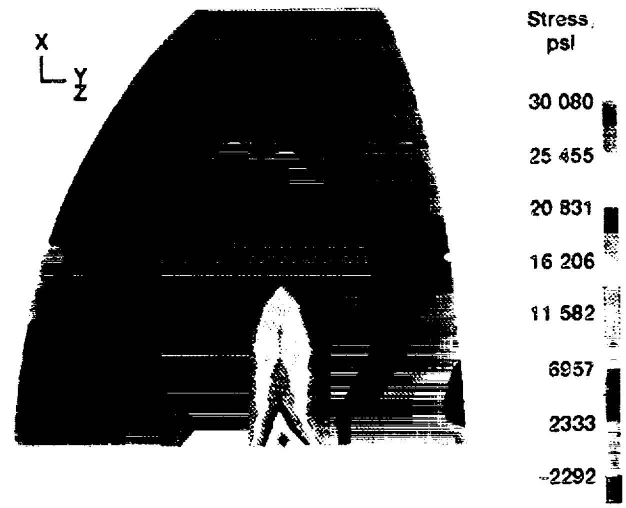


Figure 15.—CM2D-2 forward blade longitudinal stress (pressure side).

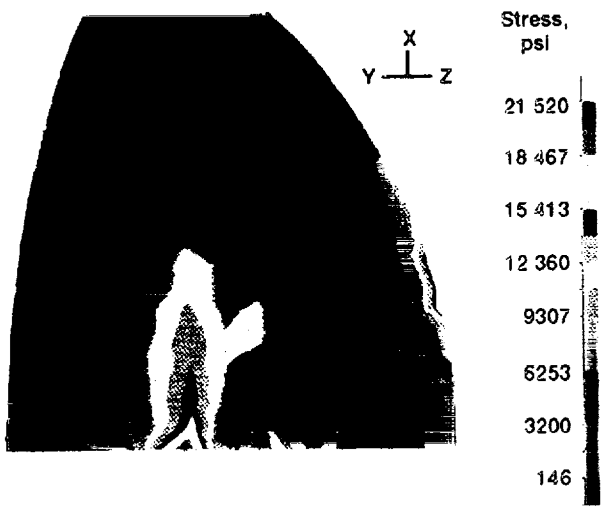


Figure 16.—CM2D-2 aft blade longitudinal stress (pressure side).

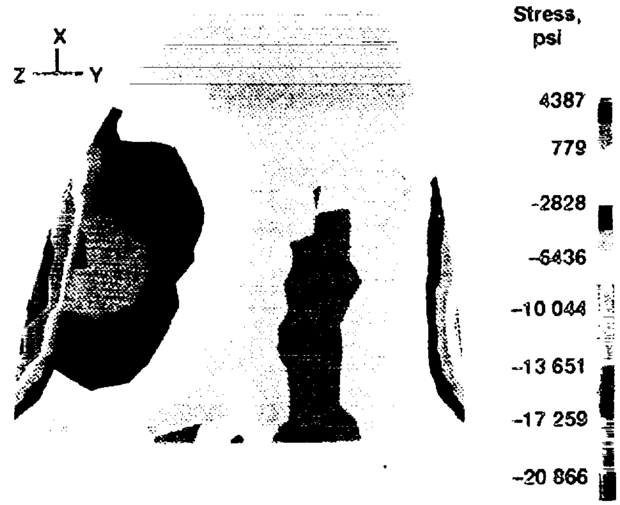


Figure 17.—CM2D-2 aft blade longitudinal stress (suction side).

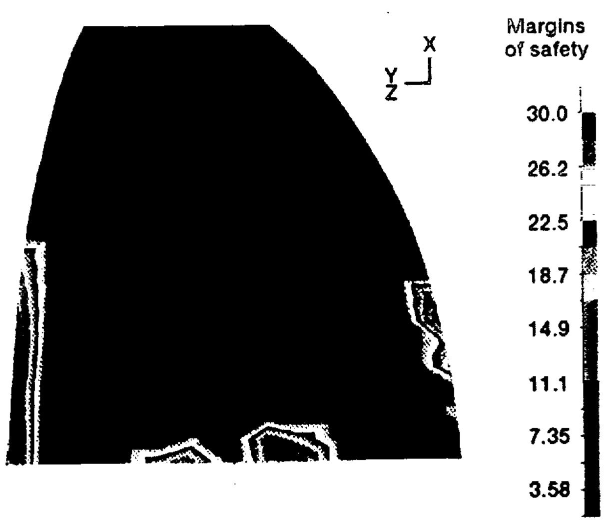


Figure 18.—CM2D-2 forward blade minimum margins of safety.

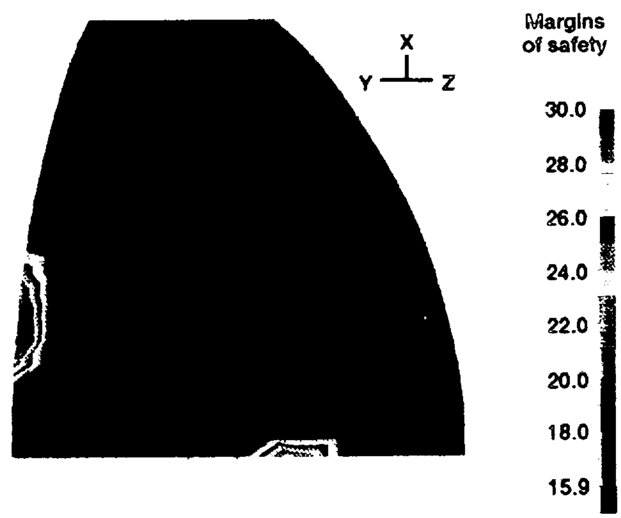


Figure 19.—CM2D-2 aft blade minimum margins of safety.

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Analyses were performed on a high-speed composite blade set for the Department of Defense Propfan Missile Interactions Project. The final design iteration, which resulted in the CM2D-2 blade design, is described in this report. Mode shapes, integral order excitation, and stress margins were examined. In addition, geometric corrections were performed to compensate for blade deflection under operating conditions with respect to the aerodynamic design shape.

**14. SUBJECT TERMS**
NASTRAN; Cruise missiles; Fan blades; Composite structures

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